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Energy Storage System Integration with Wind Generation for Primary Frequency Support in the Distribution Grid

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Abstract: With the significant increase in the insertion of wind turbines in the electrical system, the overall inertia of the system is reduced resulting in a loss of its ability to support frequency. This is because it is common to use variable speed wind turbines, based on the Double Fed Induction Generator (DFIG), which are coupled to the power grid through electronic converters, which do not have the same characteristics as synchronous generators. Thus, this paper proposes the use of the DFIG-associated Battery Energy Storage System (BESS) to support the primary frequency. A control strategy was developed, and important factors such as charging and discharging current limitations and operation within battery limits were considered. Time domain simulations have been proposed to study a distribution system containing a wind turbine, showing the advantages of BESS over frequency disturbances.

Keywords: Battery Energy Storage System; DFIG; Frequency Support; Power Systems; Wind Generation.

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1. INTRODUCTION

The increase in renewable generation sources with stochastic characteristics in the power generation matrix around the world has brought a number of challenges to the operation of the power system (Attya, Dominguez-Garcia e Anaya-Lara, 2018). This scenario replicates in the future so these sources are likely to reach ever higher levels of penetration into electrical systems.

Among the sources conventionally used in modern concepts of power generation, wind generation has gained great prominence, having already surpassed the 597 GW mark of installed capacity worldwide (WWEA, 2019). In this context, the Double Fed Induction Generator (DFIG) is certainly one of the most widespread generators today. Considering the intermittent nature of this source, the control contained in these wind generators seeks to operate it at a point that allows maximum power extraction for each wind speed (Abad *et al.*, 2011), (Bouharchouche *et al.*, 2013), (Pena, Clare e Asher, 1996).

Unlike large synchronous generators commonly used in conventional electricity generation, the active power produced by DFIG is decoupled from the grid frequency (Li *et al.*, 2014). This results in its inability to attenuate any possible disturbance in the grid using, for this, the energy contained in the rotor, as occurs in traditional generators (Miao *et al.*, 2015). In fact, as can be seen from the literature, with the increase of wind turbines in electrical systems, the overall inertia of the system is reduced which results in loss of its ability to support frequency (Gonzalez-Longatt e Alhejaj, 2016).

Several techniques have been approached to solve or mitigate this problem, where the bibliography shows that it is possible that DFIG can provide frequency support in the event of possible disturbances. Examples of techniques covered include pitch angle control, discharge control, and defining a virtual inertia. (Wu *et al.*, 2018), (Attya, Dominguez-Garcia e Anaya-Lara, 2018). In this sense, a technology that has attracted the attention of researchers and agents in the energy market is the Battery Energy Storage System (BESS) (Li *et al.*, 2014), (Serban e Marinescu, 2014), (Zhao *et al.*, 2015), (Gonzalez-Longatt e Alhejaj, 2016), (Abhinav e Pindoriya, 2016), (Attya, Dominguez-Garcia e Anaya-Lara, 2018).

Considering the need for development and improvement of frequency regulation techniques, the present work employs BESS for primary frequency support considering a distribution network with the presence of a DFIG-based wind turbine. For the development of the study, it was decided to use Matlab®/Simulink® software. The work highlights can be considered:

- BESS current limitation considering battery limits as well as maximum charge and minimum discharge limits for longer battery life;
- Use of network requirements to adjust deadband and droop parameters;
- Coordinated control between charge and discharge modes and State of Charge (SOC) to the detriment of frequency disturbances.

2. INTEGRATED DFIG AND BATTERY ENERGY STORAGE SYSTEM

The schematic diagram of the DFIG model with the BESS employed in the study is illustrated in Fig. 1. As can be seen, the topology addressed considered the use of the BESS connection directly to the DFIG AC output bus.

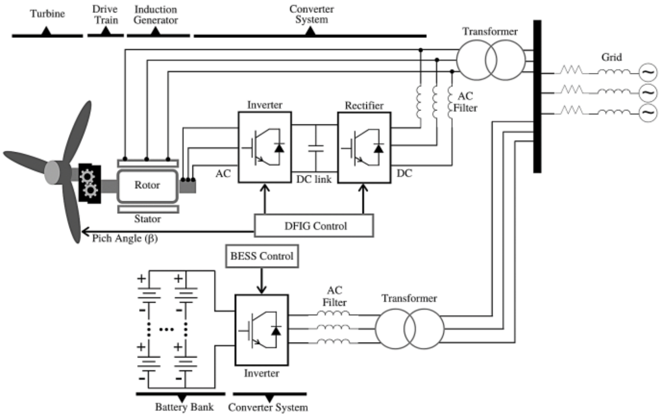

Fig. 1 DFIG diagram with BESS connected to electric grid.

2.1 Double Fed Induction Generator (DFIG)

The DFIG consists of a coiled rotor induction generator that is interconnected to the wind turbine by means of a gearbox. In this technology the stator windings are connected directly to the mains and the rotor windings to the back-to-back converter. The aspects related to modelling, control and operation of DFIG have been widely addressed in the literature (Pena, Clare e Asher, 1996), (Miller *et al.*, 2003), (Abad *et al.*, 2011). The main purpose of control systems employed in wind turbines is to maximize the energy production while protecting system components.

2.2 Battery Energy Storage System (BESS)

An energy storage system can be divided into two basic parts: the first, consisting of the storage element and the second by an energy conversion system (Gonzalez-Longatt e Alhejaj, 2016). The storage element is in charge of converting electric energy into another form of energy (electrochemical, mechanical, etc.). In this case, electrochemical batteries were employed. Regarding batteries, given the various technologies already available in the market and still others under research, this study opted for the use of Lithium-Ion batteries. Its advantages include: higher energy density, long life cycle, fast response time, low maintenance and possibility of charging and discharging several times during the day (Nadeem *et al.*, 2019), (Dehghani-Sanij *et al.*, 2019).

The lithium-ion battery bank was modeled through the Simscape Power Systems toolbox from Matlab®/Simulink® software employing the mathematical model proposed by Saw *et al* (2014).

Regarding the conversion system, for the coupling of the batteries with the DFIG it was decided to use a DC / AC converter (Inverter) connected to the AC output bus connecting to the mains. Considering the use of the system in a wind farm, this topology is more interesting from a technical and economic point of view, besides being more reliable and less complex (Muyeen *et al.*, 2009). In this sense, when the BESS connection is made through the DFIG DC link as proposed by Bouharchouche *et al* (2013) a BESS should be used for each turbine, which is an inconvenience. In addition, the physical limitation of the back-to-back converter must be considered, as it results in reduction in the amount of power that can be injected, thus making it impossible to further contribute to frequency response applications.

The strategy employed in the inverter considered the Voltage Oriented Vector Control (VOC) and the sinusoidal modulation technique with third harmonic injection (Yazdani e Iravani, 2010), (Abad *et al.*, 2011). The simplified inverter control diagram is illustrated in Fig. 2. The innermost loop of the control operates by controlling references I_d and I_q, operating in parallel, acting simultaneously on the voltage on the inverter DC link and on the grid frequency.

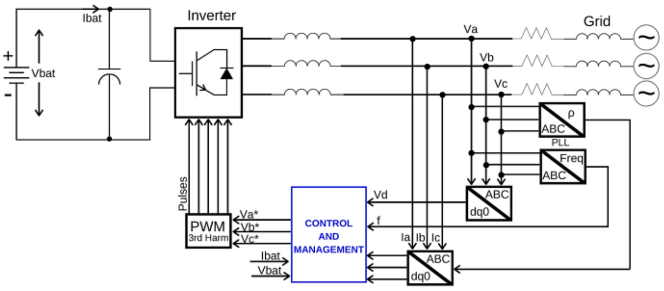

Fig. 2 BESS coupling inverter simplified block diagram.

3. BESS CONTROL FOR PRIMARY FREQUENCY SUPPORT

3.1 Active Power Command Switching (APCS)

BESS control has been integrated into the DFIG AC output to provide frequency support. In the proposed strategy, the control was coordinated with the SOC of the battery bank to protect it from the maximum (load) and minimum (discharge) limits, which provides increased equipment life (Tan e Zhang, 2017). Fig. 3 illustrates the flowchart of the control scheme employed.

In the employed control, the system will act by monitoring both the network frequency and the SOC of the batteries simultaneously. As noted in Fig. 3 there are two basic stages of operation:

1. In charge mode, the control will act, first causing the batteries to be directed to their maximum charge limit, using the power generated by DFIG. Even in charge mode, BESS can be switched to discharge mode as long as it is not below its lower limit. In this step, if there is no drop in frequency values, BESS will use the power reference (I_d_Bat) to perform system loading, changing the reference to $I_d = 0$, when it reaches its maximum load limit.

2. The discharge mode will occur in moments of frequency drop. The frequency is constantly monitored by triggering the BESS unloading to compensate for the frequency in case of disturbances. At this time, the power reference will be switched to

discharge (I_d_Pot) and will continue to deliver active power to the grid until the minimum load limit is detected. If BESS reaches its lower limit, the power reference will change to I_d = 0, where the system stops delivering power to the grid.

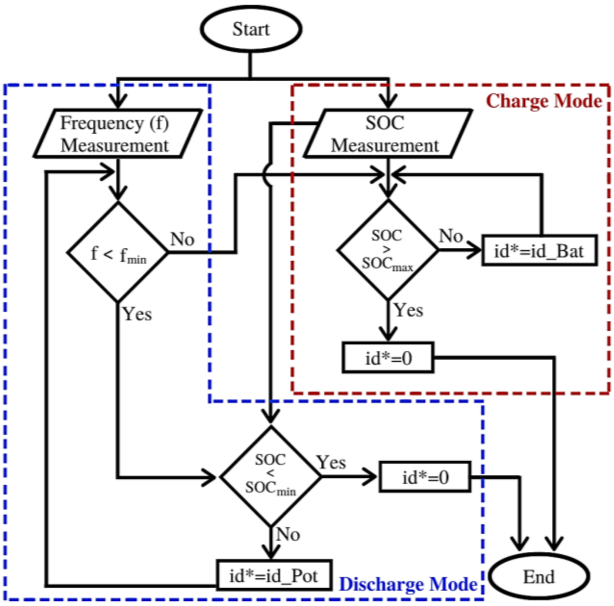

Fig. 3 BESS control scheme flowchart for frequency support.

3.2 Power Control (Discharge Mode)

As can be seen in Fig. 4, the control employed used an internal circuit to control the discharge of the batteries and an external circuit responsible for monitoring and controlling the frequency.

The frequency will be constantly measured and compared to the reference (60 Hz). The deadband has been set to 0.1 Hz and this signal is then controlled by a droop gain where the frequency will be converted to power reference (Gomez *et al.*, 2019). In the internal loop the discharge control was performed, using a Proportional and Integral (PI) type controller. To adjust the deadband and droop parameters, the Electric Power Distribution Procedures in the National Electric System (PRODIST, in its Portuguese acronym) were used (ANEEL, 2018).

Subsequently, the generated signal will be the reference of the current (I_d_Pot) being employed according to the APCS described in the previous section and observed in Fig. 3.

3.3 SOC Control (Charge Mode)

This control loop is also illustrated in Fig. 4. The internal loop has the purpose of controlling the charge of the battery bank and the external loop is responsible for regulating the voltage on the DC bus of the batteries and also for keeping the SOC within the maximum and minimum limits.

In this case the DC bus voltage (V_{dc}_bat) will be monitored to ensure system stability. A PI controller was then applied for regulation and then the battery operating limits are employed. As noted in the literature, it is important that the batteries are operating within the proper operating range to ensure long life (Tan e Zhang, 2017). So, the minimum discharge limit considered was 20% and the maximum load 70%. In the internal loop load control is performed and a PI controller was also used.

The generated signal will be the battery current reference (I_d_Bat) that will be used in the current control block according to the APCS described in the previous section and observed in Fig. 3.

4. TESTS AND RESULTS

In order to study the impact of the proposed solution as well as the control method as a way to assist the electrical system in restoring the frequency in case of faults, the test system illustrated in Fig. 5 is proposed. Such system represents the follow-up of a distribution network where the 2.5 MW capacity DFIG is interconnected to the 1.5 MW capacity BESS via bus 3. In this work, aiming to highlight the contribution of BESS in frequency regulation, it was considered, for all cases, a SOC of 70 %, where BESS is considered fully charged.

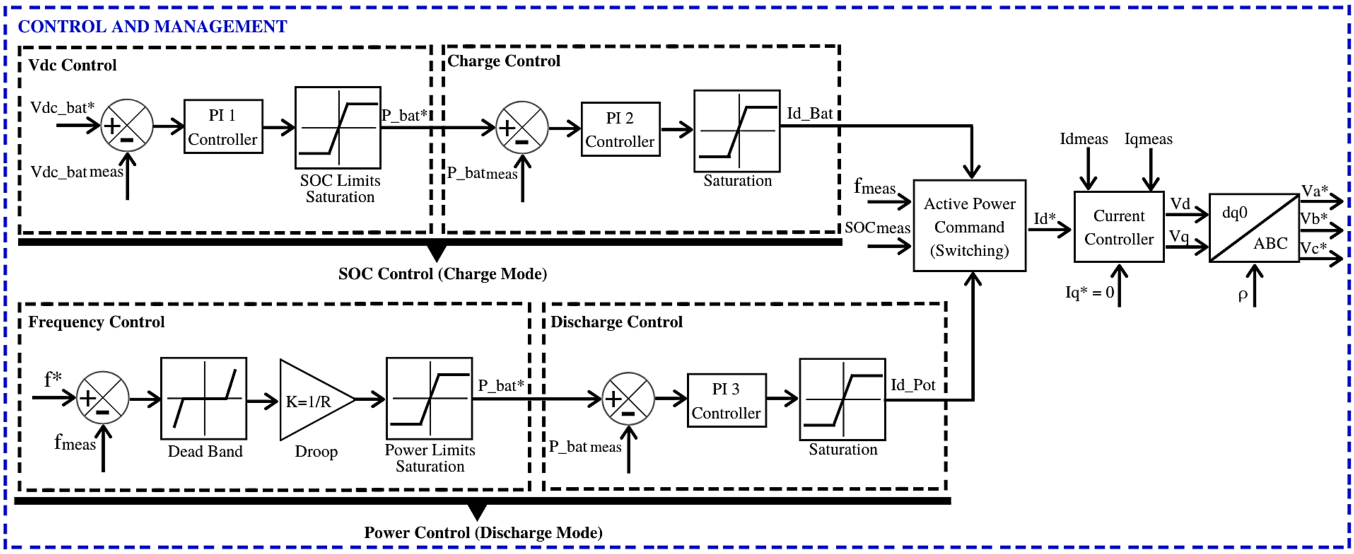

Fig. 4 Proposed control strategy block diagram.

It was considered a small 7.5 MW hydroelectric power plant connected to bus 7 and equivalent network of 500 MVA short-circuit power connected to bus 6. It is important to note that the load considered in bus 4 will be described as to its power, in the case studies presented in the following subsections, since variations were considered in order to simulate scenarios of higher and lower demand.

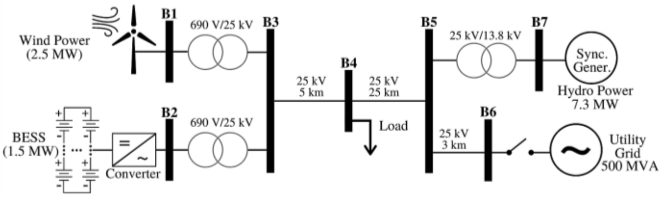

Fig. 5 Test distribution system diagram.

Considering the previous, for eventual moments of frequency increase, DFIG itself can act reducing the power delivered to the electric network, the present work only dealt with the frequency drop events, since they are more common in the electric power systems (Miao *et al.*, 2015). To analyze the results regarding the frequency behavior, it was considered the network requirements established by the regulation employed in Brazil (ANEEL, 2018).

4.1 Case 1 – Disconnection with Utility Network Considering Lower Demand

Firstly, it was considered the disconnection of Bar 6 in relation to the electric grid, as illustrated in Fig. 5. In this case the simulation time was 15 s, and the output of the grid occurs at 2.5 s, remaining disconnected for the remainder of the grid simulation. In this case, the load considered in bus 4 has a power of 10.3 MW. Wind speed for wind generation was kept constant at its nominal value (11.5 m/s), where DFIG delivers a power of 2.5 MW.

The first analysis to be performed concerns the system frequency as illustrated in Fig. 6 where the comparison with and without the presence of BESS is presented. Without BESS, the frequency dropped, remaining between 58.5 and 59.5, thus below the normal operating condition limit allowed by the standard considered in this paper. In this operating range, the frequency could have a permanence time of 30 s where it is dependent thereafter on secondary and tertiary frequency controls for its re-establishment (ANEEL, 2018). As can be seen, BESS causes the frequency has returned to its nominal value within the normally allowed deadband, which shows BESS contribution to frequency regulation.

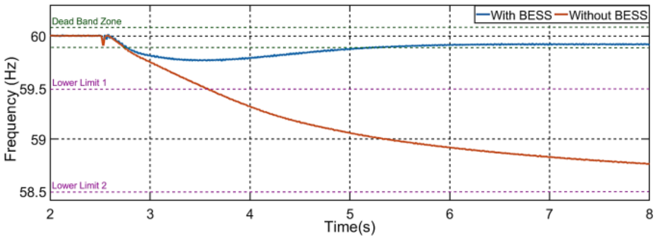

Fig. 6 System frequency with and without BESS for case 1.

For the same case, BESS power control is illustrated in Fig. 7. Looking at this figure together with Fig. 6 it can be seen that at 2.5 s the system suffered a frequency fluctuation, where BESS acted by injecting the power proportional to the frequency variation that is determined by the droop control.

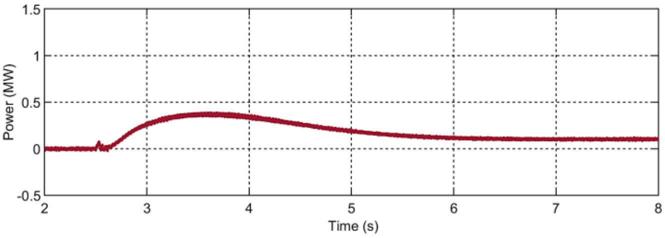

Fig. 7 BESS power control for case 1.

4.2 Caso 2 – Disconnection with Utility Network Considering Higher Demand

Similarly, to the previous case, considering the variability of the charging level of the electrical system, in this case, the load considered in bus 4 was parameterized with power of 11.1 MW. Wind velocity for wind generation was kept constant, with the nominal generation as in the previous case. Also, regarding to the disconnection of the network, the switching occurred at 2.5 s, with simulation time of 15 s, as previously implemented.

In this case, the higher load scenario directly influenced the frequency variation in case of loss of grid connection, as observed in Fig. 8.

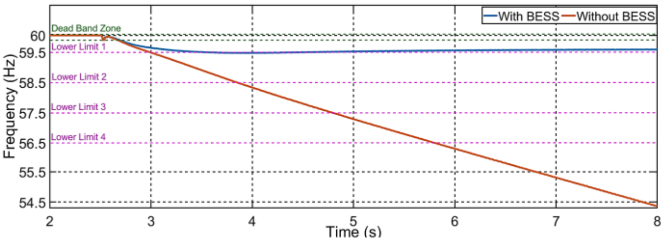

Fig. 8 System frequency with and without BESS for case 2.

Without BESS the frequency falled below the lowest limit allowed by the norm (56.5 Hz), which would imply the protection system actuation (not considered in this work), causing the system to collapse. Already with BESS, it was possible to reset the frequency above the upper limit 1, where the length of stay, according to the standards considered, is 30 s. Since the purpose of the control proposal was to perform primary frequency support, it is noted that BESS fulfilled its purpose by limiting the frequency drop. However, it would be necessary to correct the frequency value to the nominal value, but from that moment on, the system secondary and tertiary frequency controls would be required to restore normality (controls not covered in this paper).

The power of BESS is shown in Fig. 9. Taking this figure and Fig. 8 together, it is noted that at 2.5 s the frequency decay occured, where BESS acted by injecting the power proportional to the frequency variation. In this case, BESS needed to act by injecting a greater amount of power to contribute to the electrical system.

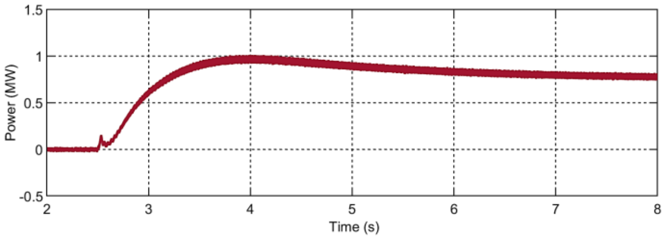

Fig. 9 BESS power control for case 2.

4.3 Caso 3 – Wind Generation Variation

One of the critical situations for frequency in a wind generation distribution system is when there is variation in generation caused by fluctuations in wind speed, which is quite common in renewable sources. In this sense, the present case study considered a variation in wind speed as illustrated in Fig. 10. The simulation time considered was 20 s, and the grid remained connected throughout the simulation time.

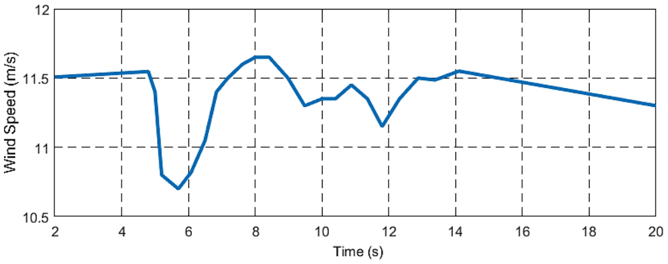

Fig. 10 Wind speed profile considered in case 3.

The power behavior generated by DFIG is illustrated by Fig. 11.

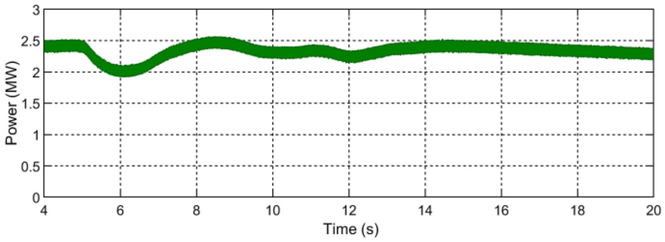

Fig. 11 Power generated by DFIG for case 3.

The system frequency is shown in Fig. 12. In this case, it is important to note that in both cases, the system re-establishes the frequency as it approaches 20 s. At the most critical point of the power change (occurring between 5 and 14 s), without BESS, the frequency falled below the first lower limit, where the system would have 30 s to recover, but wind speed returned to normal, thus contributing to the readjustment of the system. However, with BESS the frequency oscillation was considerably smaller, being practically kept within the allowed oscillation zone.

Finally, the power of BESS is shown in Fig. 13 where one can perceive the actuation of the control by injecting power into the system to compensate for the frequency oscillations that occurred during the simulation.

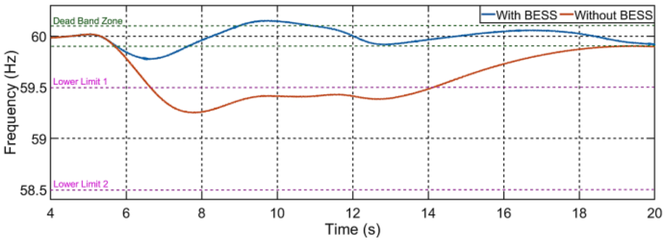

Fig. 12 System frequency with and without BESS for case 3.

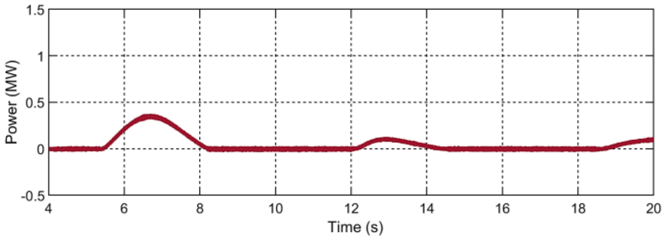

Fig. 13 BESS power control for case 3.

5. CONCLUSIONS

In the present work it was proposed the integration of a BESS to wind generation as a way to promote primary frequency support to the distribution network. In this sense, scenarios were shown that show situations where the system frequency suffers instabilities to the point of extrapolating the limits established by norm. As can be seen from the results presented, BESS was able to act positively by mitigating the effect, thus contributing to the adjustment of the primary frequency.

The proposed control method proved to be effective, being evidenced by the active power injection used for the necessary frequency compensation. In times of lower demand, BESS can help by helping to return the frequency to normal. In higher demand scenarios, BESS helps limit the frequency drop to prevent system collapse in conjunction with the electrical system that can provide secondary and tertiary frequency support for full system re-establishment.

In this paper, the results regarding the frequency analysis were reported, but the developed model addresses many other aspects that have not been described, which will be presented in future works. Still in future works, the publication of the advance in the development of controls to contribute to the regulation of secondary and tertiary frequency is reported.

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